Z-Source with Voltage Multiplication Inverter for Grid-Tie Photovoltaic Applications

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Abstract— **this paper proposes Z-source with voltage multiplication inverter for grid connected Photovoltaic (PV) application. The proposed scheme has two-stage. The first stage consists of Z-source with voltage multiplication converter. The proposed converter has high gain compared to other transformer less topologies and reduced voltage stress on the switch. The second stage assembled from five switch inverter. The purpose of the first stage is to boost the low voltage of the PV module to a voltage level suitable for grid connection and controls the PV modules at Maximum Power Point (MPP). The second stage used to convert DC voltage into AC voltage and inject sinusoidal current with unity power factor into the grid. Model Predictive Control (MPC) is proposed to control the proposed system. MPC has some inherent advantages such as fast tracking, very small settling time and ease of implementation.**

Keywords— Model Predictive Control; Z-source with voltage multiplication inverter; Maximum Power Point (MPP); single-phase; PV applications.

I. INTRODUCTION

The developing apprehension about the remaining fossil fuel reserves and the environmental aspects has given a high motivation to the use of renewable energy sources in power generation. Correspondingly the rate at which the request for electrical energy is increasing, limits the planning and installation of large, centralized power plants, resulting in distributed energy sources and power generation. The high cost of these sources, particularly the unconventional ones, has encouraged major efforts in the development of efficient and low cost power conditioning units to serve as an interface between the source and the grid. The power conditioning unit conditions the source energy appropriately to meet the grid requirements. Indeed, a power conditioning unit forms an integral part of any distributed generation system[1]-[11].

Grid connected photovoltaic (PV) arrangements frequently contain a line transformer between the conversion stage and the grid. The transformer warranties galvanic isolation between the grid and the PV system, thus fulfilling safety standards. Furthermore, it significantly decreases leakage currents between the PV system and the ground and guarantees that no direct current (DC) is injected into the grid. However, because of its low frequency (50-60 Hz), the transformer is big, heavy, and expensive. Because of the cost and size reduction and overall efficiency improvement, the consideration on transformerless conversion topologies is increasing. Depending on the number of stages between input and output, inverters could be classified as single stage or two stage inverters. Inverters can be buck inverters, boost inverters, or buck-boost inverters. Single-Stage inverter consists of only one stage. The function of this stage is to 1) extract maximum power from PV module, 2) boost low DC output voltage to a high voltage level and 3) inject a sinusoid with a low THD in case of grid connection. And two stage inverter consists of two stages, the first stage includes DC/DC converter to boost the voltage and the second stage contains DC/AC converter convert from DC voltage into AC voltage [7]-[11].

This paper proposes z-source with voltage multiplication inverter for grid connected PV applications. The proposed system consists of two stages, as depicted in Fig. 1. The first stage is the proposed high gain z-source with voltage multiplication converter. High gain z-source with voltage multiplication converter is used to boost the low voltage of the PV module and extract the maximum power from it. And the second stage is a five switch with low switching losses inverter, used to interface the PV module into the grid. The control technique which is proposed to control the proposed power stage is the finite-set Model Predictive Control (MPC). Model Predictive Control (MPC) is very fast, accurate controller, and its implementation is simple[12]-[19]. The main point of the MPC is to create a model for the controlled system, for prediction of the controlled variable and selection of optimum operation according to the specified cost function. Cost function determines the required control criteria[18]-[19]. The proposed system is controlled to do the following functions: extract maximum power from photovoltaic module, boost the low output voltage of the PV module and control the current injected into the grid to be sinusoidal and in phase with the grid voltage.

II. Z-SOURCE CONVERTER

Figure. 2 displays the common Z-source converter construction [12]-[14]. It employs an exclusive impedance network to pair the converter main circuit to the power source, load, or another converter, for providing distinctive features that cannot be detected in the traditional V and I-source converters where a capacitor and inductor are used respectively.

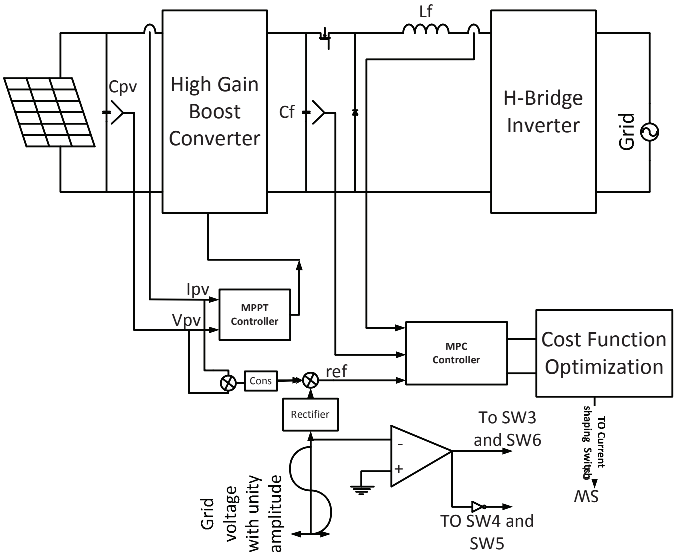

Fig. 1. Configuration of the proposed system.

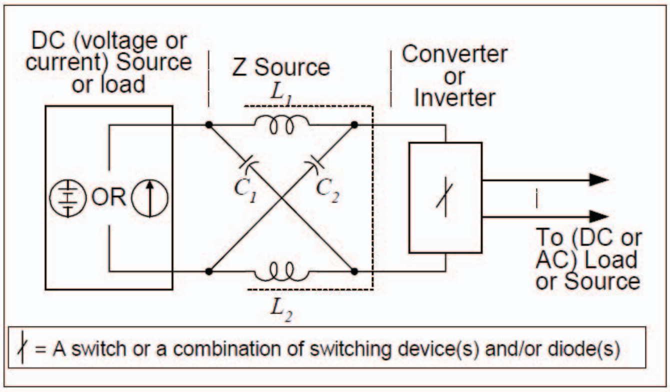

Fig. 2. A general structure of the Z-source converter.

The Z-source converter overcomes the concrete and theoretical obstacles and boundaries of the traditional V-source converter and I-source converter and provides a novel power conversion concept. In Fig. 3, a two-port network that consists of a split inductor L1 and L2 and capacitors C1 and C2 connected in X shape is employed to offer an impedance source (Z-source) coupling the converter (or inverter) to the dc source, load, or another converter. The dc source /or load can be either a voltage or a current source /or load. Therefore, the dc source can be a battery, diode rectifier, thyristor converter, fuel cell, an inductor, a capacitor, or a combination of those. Switches used in the converter can be a combination of switching devices and diodes such as the anti-parallel combination as shown in Fig. 1, the series combination as shown in Fig. 2, etc. For examples, Figs. 4 and 5 show two 3-phase Z-source inverter configurations. The inductance L1 and L2 can be provided through a split inductor or two separate inductors. The Z-source concept can be applied to all dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion. To describe the operating principle and control, this paper focuses on an application example of the Z-source converter: a Z-source inverter for dc-ac power conversion needed for fuel cell applications. Even though the Z-source converter overcomes the conceptual and theoretical barriers and limitations of the traditions voltage source and current source converters and provides a novel power conversion concepts it suffers from many disadvantages.

1) The input DC current is discontinuous in Z-source converter and has high ripple in the output voltage.

2) High voltage stress across the switches

3) It has less voltage boost factor which is not sufficient in photovoltaic applications.

III. Principle of Operation of Z-Source with Voltage Multiplication Converter

In this paper z-source with voltage multiplication converter for PV application, the proposed converter is depicted in Fig. 3. The proposed converter has some inherent advantages such as very high gain compared to other converters exist in the literature, low voltage stress on the switch and operates in Continuous Conduction Mode (CCM). As the converter operates in CCM, this cause the converter to have two modes of operation.

Mode 1 take place when switch SW is triggered to be ON, this mode is depicted in 0 Fig. 3 (b). Turning on switch SW causes diode D2 to have forward voltage so it becomes ON.

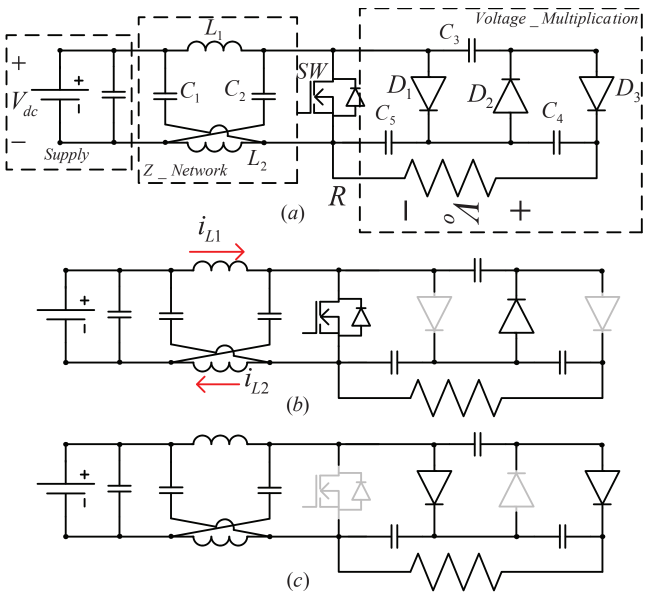

Fig. 3. Z-source with voltage multiplication converter. (b) Mode 1 (c) mode 2.

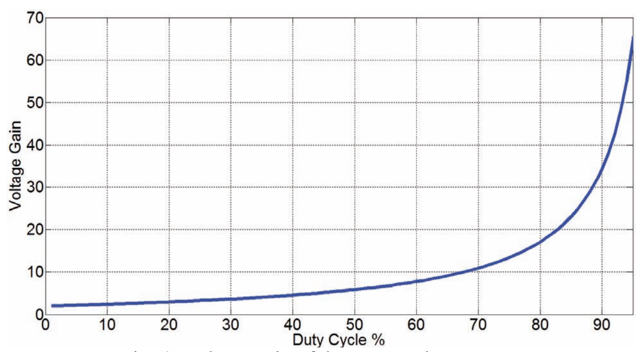

Fig. 4. Voltage gain of the proposed converter.

While diodes D1 and D3 have reverse voltages and become OFF. The main descriptive equations of this mode is as follow:

$$V_{c1} = V_{c2} = V_C \quad (1)$$

$$v_{l1}(t) = v_{l2}(t) = V_g + V_C \quad (2)$$

$$v_{c5}(t) = v_{c4}(t) = v_{c3}(t) = \frac{V_o}{2} \quad (3)$$

Mode 2 1 take place when switch SW is triggered to be OFF, this mode is depicted in Fig. 3 (c). Turning OFF switch SW causes diode D2 to have reverse voltage so it becomes OFF too. While diodes D1 and D3 have forward voltages and become ON. The main descriptive equations of this mode is as follow:

$$v_{l1}(t) = v_{l2}(t) = (V_C - \frac{V_o}{2}) \quad (4)$$

$$v_{c5}(t) = v_{c4}(t) = v_{c3}(t) = \frac{V_o}{2} \quad (5)$$

Applying inductor voltage second balance and capacitor charge balance, the voltage gain of the proposed inverter could be obtained as follow:

$$V_g * D + V_C * \mathrm{D} + V_C * (1 - \mathrm{D}) - \frac{V_o}{2} * (1 - D) \quad (6)$$

$$\frac{V_o}{V_g} = M = \frac{2*(D+1)}{(1-D)} \quad (7)$$

The voltage gain of the proposed converter is given by equation (7) and depicted in Fig. 4. Figure. 4 depicts the relation between the voltage gains of the proposed converter versus duty cycle percentage. The proposed converter has high gain compared to traditional z-source converter. Though having higher gain, the voltage stress on the switch of the proposed converter is half of that of the traditional z-source converter at the same voltage gain.

IV. MODEL PREDICTIVE CONTROL OF THE PROPOSED INVERTER

The main distinctive of MPC is predicting the future behavior of the anticipated control variables until a redefined horizon in time. The predicted variables will be used to acquire the optimal switching state by minimizing the cost function. At each sampling time, the optimization problem is solved again by using a new set of measured data to obtain a new sequence of optimal actuation. The MPC principle of working is illustrated graphically in Fig. 5. Fig. 5 clearly illustrates the essential properties of the model predictive control strategy. All potential system transitions $y_{Pn}(K+1)$ can be predicted using the discrete-time model of the system for all control actions (or the time horizon) of N (N = 1, 2, 3, . . . , n). Take N = 1 as an example; the system behavior at k + 1 instant can be predicted with the measured value y(k) and n possible voltage vectors, resulting in n possible values $y_{P1},\ y_{P2},\ \dots\dots y_{Pn}$.

Now, assume that y_{P2} is flanking to y^*; the voltage vector generating y_{P2} will be selected and applied between the k and (k + 1) instants. The MPC for power electronics converters can be designed using the following steps:

1) Modeling of the power converter recognizing all possible switching states and its relation to the input or output voltages or currents;

2) Outlining a cost function that signifies the preferred behavior of the system;

3) Procurement discrete-time models that permit one to predict the future behavior of the variables to be controlled.

The proposed inverter topology involves five switches. Even though it has five switches, only one switch functions at high switching and the rest activates at fundamental frequency. Switch SW_2 is controlled to inject a sinusoidal current into the grid with unity power factor. The proposed inverter has two modes of operation depends on the states of switch SW_2. First mode1 when switch SW_2 is on and the second mode take place when SW_2 is off. Operation modes of the proposed inverter depicted in to control the proposed inverter a model is created for the proposed inverter, depicted in Fig. 6 (a). The proposed inverter has two model configuration, one when SW2 is ON, Fig. 6 (b), and the second configuration when SW2 is OFF Fig. 6 (c).

Mode 1: This mode take place when Sw2, SW3 and SW4 are on D, SW5 and SW5 are off. Applying Kirchhoff's voltage law as follow;

$$L_f \frac{di_{Lf}(t)}{dt} + i_{Lf}(t) * R_f + V_g - V_{cf} = 0 \quad (8)$$

Mode 2: This mode take place when D, SW5 and SW5 are on Sw2, SW3 and SW4 are off. Applying Kirchhoff's voltage law as follow;

$$L_f \frac{di_{Lf}(t)}{dt} + i_{Lf}(t) * R_f + V_g = 0 \quad (9)$$

Rearranging the equations

$$L_f \frac{di_{Lf}(t)}{dt} = V_{cf} - i_{Lf}(t) * R_f - V_g \quad (10)$$

$$L_f \frac{di_{Lf}(t)}{dt} = -i_{Lf}(t) * R_f - V_g \quad (11)$$

Using the discrete form of the current equation is as follows:

$$\frac{\mathrm{di}_{Lf}}{\mathrm{dt}} = \frac{\mathrm{i}_{Lf}(\mathrm{k+1}) - \mathrm{i}_{Lf}(\mathrm{k})}{\mathrm{T_S}} \quad (12)$$

The equation for predicting the load current is obtained from substituting (12) into (10) and (11), and the resulting equation is as follow:

$$I_{Lf,1}(k+1) = \frac{T_S}{L} * V_{cf} - \frac{T_S}{L} * V_g + I_{Lf}(k)(1 - \frac{T_S * R_f}{L_f}) \quad (13)$$

$$I_{Lf,0}(k+1) = I_{Lf}(k)(1 - \frac{T_S * R_f}{L_f}) - \frac{T_S}{L} * V_g \quad (14)$$

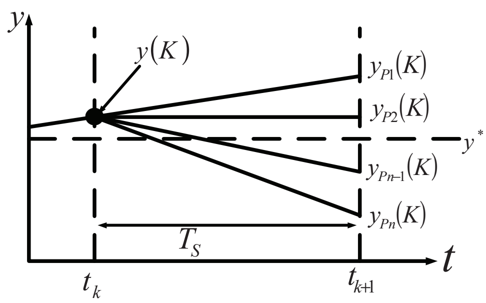

Fig. 5. MPC principle of working.

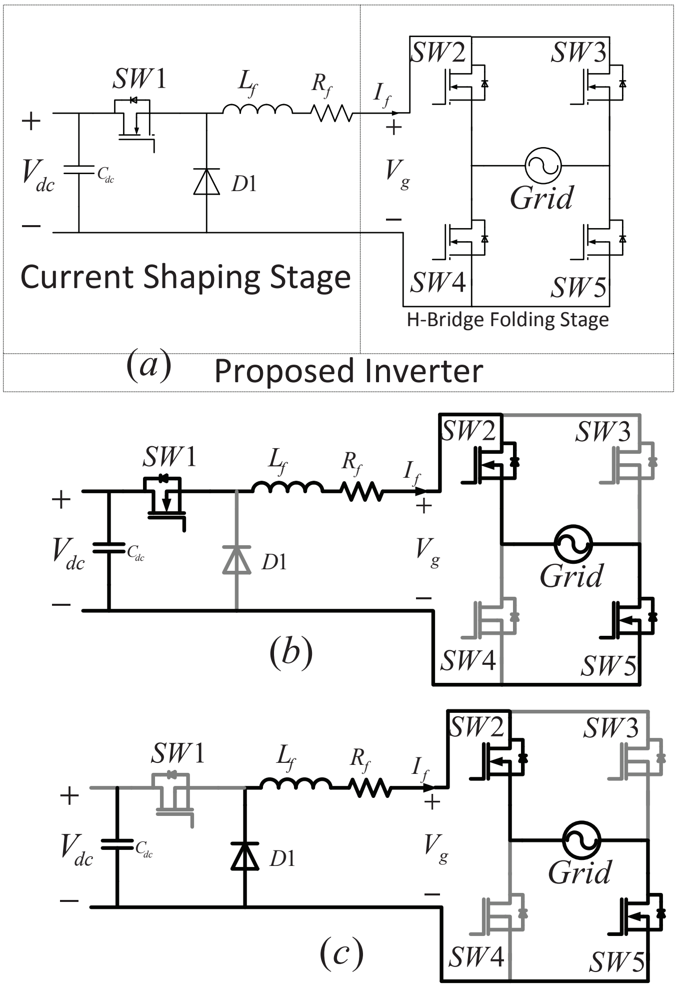

Fig. 6. (a) Proposed inverter model (b) Mode 1 model (c) mode 2 model.

The key parameter of the MPC is the cost function as it determines the required control functions. In the proposed system the required control function is to control the amplitude and frequency of the current injected into the grid. For the required control criteria for the proposed system the cost function is given as;

$$G_1 = |I_{Lf,1} - I_{ref}| \quad (15)$$

$$G_0 = |I_{Lf,0} - I_{ref}| \quad (16)$$

Where L_f, T_s, R_f, V_g, V_{cf}, $I_{Lf}(k)$, $I_{Lf,1}(k+1)$, $I_{Lf,0}(k+1)$, G_1, G_0 and I_{ref} are the filter inductance, sampling time, filter leakage resistance, rectified grid voltage, input capacitor voltage, current inductor current, predicted inductor current when the switch is turned on, predicted inductor current when the switch is turned off, cost function when switch is on, cost function when switch is off and reference current generated by the MPPT control respectively. Generation of the reference current depends on the MPPT algorithm operation. PV output voltage and current are measured via MPPT control technique then MPPT algorithm generate pulses for the high gain boost converter and the reference current for the MPC algorithm. Algorithm of the proposed control technique is figured out in Fig. 7. Rectified grid voltage, filter capacitor voltage, inductor current and reference current are measured.

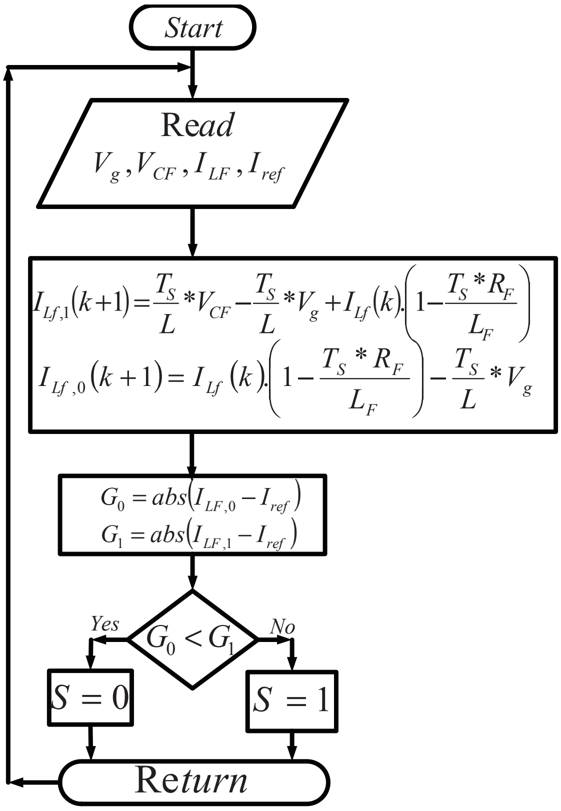

Fig. 7. Proposed MPC Algorithm.

After measuring the required parameter, equations (13) and (14) are calculated for calculating the predicted inductor current in both mode1 and mode 2. Cost functions in mode 1 and mode 2 are calculated then compared together. The state of the switch depends on the cost functions. If G_0 is lower than G_1 then the switch is off, else it's turned on.

V. SIMULATION

Table I Provides the characteristics of the PV module used in the simulation. Four modules were used in the simulation. PSIM software is a powerful simulation tool and it is used for system operation demonstration. To authenticate the operation of the proposed algorithm, solar irradiation was changed from 700 [W/m^2] to 1000 [W/m^2] at 1.5 Sec. According to table I, output power should be 340 W at 1000 [W/m^2]. As depicted in Fig. 8, the proposed controller is able to track the maximum power at different radiations and reaches to steady states at very small time.

As the output power of the PV module is variable according to the environmental conditions, the amplitude of the current injected into the grid is changing accordingly. MPC showed it is robustness in case of fast amplitude change with less oscillation and small transient time. The whole system is simulated used PSIM software. Figure 9 is a depiction of the grid voltage and the current injected into the grid in case of using PI controller and MPC. This figure is a comparison between PI controller and MPC. As shown in Figs. 9 and 10 the performance of MPC controller is promising. MPC controller reaches to steady states faster than PI controller and it suffers from less oscillations compared to PI controller.

Table I
PV Module Characteristic

Electrical Characteristics	BP 485
Maximum power (Pmax)	85W
Voltage at Pmax (Vmp)	17.8V
Current at Pmax (Imp)	4.9A
Warranted minimum Pmax	80.75W
Short-circuit current (Isc)	5.4A
Open-circuit voltage (Voc)	22.0V
Temperature coefficient of Isc	(0.065±0.015)%/ °C
Temperature coefficient of Voc	-(80±10)mV/°C

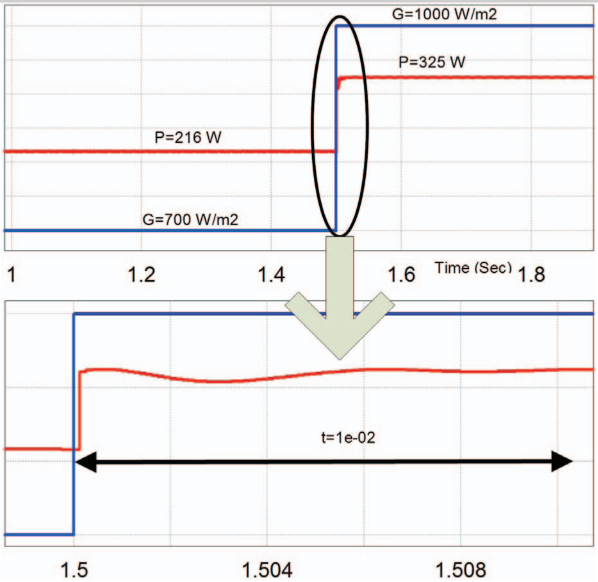

Fig. 8. PV output power with proposed algorithm.

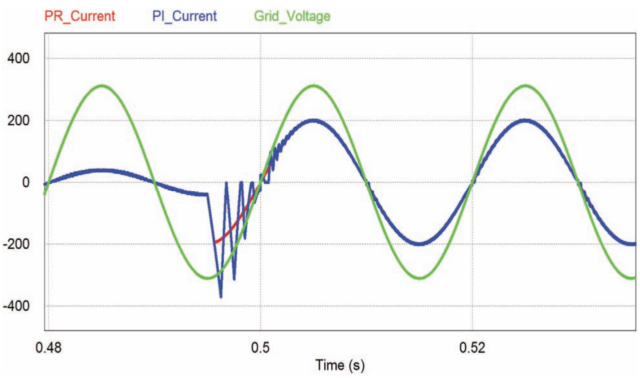

Fig. 9. Grid Voltage and grid current with a step change in reference with PI and MPC.

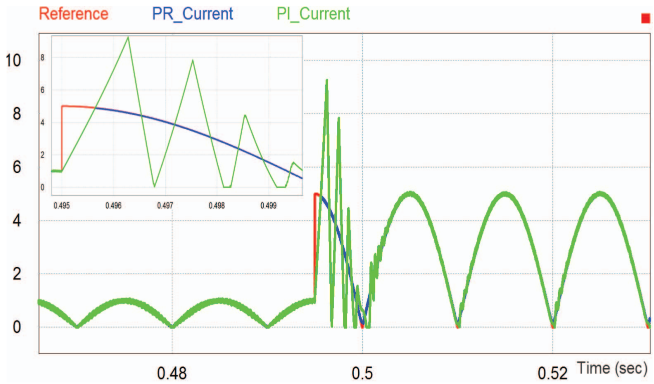

Fig. 10. Reference current and measured current with PI and MPC.

Conclusion

Z-source with voltage multiplication inverter for grid connected PV application was proposed. The proposed system had two-stage. The first stage consisted of Z-source with voltage multiplication converter. The proposed converter had high gain compared to other transformerless topologies and lesser voltage stress on the switch. The second stage constructed from five switch inverter. Model predictive control was proposed to control the proposed system. MPC had some inherent advantages such as fast tracking, very small settling time and ease of implementation. Simulation and experimental results were discussed through the paper to validate the proper operation of the proposed system.

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